

Theory News on $B_{s(d)} \rightarrow \mu^+ \mu^-$ Decays

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Abstract: The rare decays $B_{s(d)} \rightarrow \mu^+ \mu^-$ play a key role for the testing of the Standard Model. An overview of the most recent theoretical predictions of the corresponding branching ratios is given, emphasizing that the sizable decay width difference $\Delta\Gamma_s$ of the B_s -meson system affects the $B_s \rightarrow \mu^+ \mu^-$ channel. As a consequence, the calculated Standard Model branching ratio has to be upscaled by about 10% to $BR(B_s \rightarrow \mu^+ \mu^-) = (3.54 \pm 0.30) \times 10^{-9}$. This prediction is the reference value for the comparison with the time-integrated experimental branching ratio, where LHCb has recently reported $(3.2^{+1.5}_{-1.2}) \times 10^{-9}$ corresponding to the first evidence for $B_s \rightarrow \mu^+ \mu^-$. The $\Delta\Gamma_s$ effects have also to be included in the constraints on the parameter space of New-Physics models following from the experimental data. Furthermore, $\Delta\Gamma_s$ makes a new observable through the effective $B_s \rightarrow \mu^+ \mu^-$ lifetime accessible, which probes New Physics in a way complementary to the branching ratio and adds an exciting new topic to the agenda for the high-luminosity upgrade of the LHC.

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1 Introduction

The rare $B_{s(d)} \rightarrow \mu^+ \mu^-$ decays receive only loop contributions from box and penguin topologies in the Standard Model (SM). Moreover, as only leptons are present in the final states, the hadronic sectors are very simple, involving the $B_{s(d)}$ decay constants $f_{B_{s(d)}}$. These transitions with their strongly suppressed rates offer hence powerful probes to search for footprints of “New Physics” (NP) originating from beyond the SM (see [1] and references therein).

The most recent theoretical updates of the branching ratios read as follows [2]:

$$BR(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}} = (3.23 \pm 0.27) \times 10^{-9} \quad (1)$$

$$BR(B_d \rightarrow \mu^+ \mu^-)_{\text{SM}} = (1.07 \pm 0.10) \times 10^{-10}, \quad (2)$$

where the errors are dominated by those of lattice QCD determinations of the non-perturbative $f_{B_{s(d)}}$ decay constants [3].

The limiting factor of the measurement of the $B_s \rightarrow \mu^+\mu^-$ branching ratio at hadron colliders is also due to a non-perturbative quantity, the ratio f_s/f_d of the fragmentation functions f_q describing the probability that a b quark fragments in a \overline{B}_q^0 meson. A new method for determining f_s/f_d using nonleptonic $\overline{B}_s^0 \rightarrow D_s^+\pi^-$, $\overline{B}_d^0 \rightarrow D^+K^-$, $\overline{B}_d^0 \rightarrow D^+\pi^-$ decays [4, 5] was recently implemented at LHCb [6], resulting in good agreement with measurements using semileptonic decays [7]. The $SU(3)$ -breaking form-factor ratio entering the non-leptonic method has recently been calculated with lattice QCD [3, 8].

In November 2012, LHCb has reported the first evidence for $B_s^0 \rightarrow \mu^+\mu^-$ at the 3.5σ level, with the following branching ratio [9]:

$$\text{BR}(B_s \rightarrow \mu^+\mu^-) = (3.2_{-1.2}^{+1.5}) \times 10^{-9}, \quad (3)$$

and the upper limit of $\text{BR}(B_d \rightarrow \mu^+\mu^-) < 9.4 \times 10^{-10}$ (95% C.L.). These results complement previous constraints from the CDF, D0, ATLAS and CMS collaborations discussed at this workshop (for a recent experimental review, see [10]).

In spring 2012, LHCb announced another interesting result on a – seemingly – unrelated topic, a sizable width difference $\Delta\Gamma_s$ of the B_s -meson system [11]:

$$y_s \equiv \frac{\Delta\Gamma_s}{2\Gamma_s} \equiv \frac{\Gamma_L^{(s)} - \Gamma_H^{(s)}}{2\Gamma_s} = 0.088 \pm 0.014, \quad (4)$$

where Γ_s is the inverse of the average B_s lifetime τ_{B_s} . A sizable value of $\Delta\Gamma_s$ was theoretically expected since decades (for a review, see [12]).

The significant decay width difference $\Delta\Gamma_s$ leads to subtleties in the interpretation of experimental data on B_s decays in terms of branching ratios calculated from theory [13] (see also [14, 15]). This concerns, in particular, the $B_s \rightarrow \mu^+\mu^-$ decay [16], where the impact of $\Delta\Gamma_s$ had so far not been taken into account in the relevant analyses. Moreover, this quantity offers another theoretically clean observable, the effective lifetime of the $B_s \rightarrow \mu^+\mu^-$ channel, which is complementary to the branching ratio.

In the case of the $B_d \rightarrow \mu^+\mu^-$ decay, this phenomenon is not of practical relevance as the decay width difference $\Delta\Gamma_d$ of the B_d -meson system has a tiny value of $\Delta\Gamma_d/\Gamma_d \sim 10^{-3}$ in the SM [12].

2 Observables

Using the same notation as in [17], the low-energy effective Hamiltonian describing the $\overline{B}_s^0 \rightarrow \mu^+\mu^-$ decay can be written as

$$\mathcal{H}_{\text{eff}} = -\frac{G_F}{\sqrt{2}\pi} \alpha V_{ts}^* V_{tb} [C_{10}O_{10} + C_S O_S + C_P O_P + C'_{10}O'_{10} + C'_S O'_S + C'_P O'_P]. \quad (5)$$

Here the short-distance physics is encoded in the Wilson coefficients C_i , C'_i of the four-fermion operators

$$O_{10} = (\bar{s}\gamma_\mu P_L b)(\bar{\ell}\gamma^\mu\gamma_5\ell), \quad O_S = m_b(\bar{s}P_R b)(\bar{\ell}\ell), \quad O_P = m_b(\bar{s}P_R b)(\bar{\ell}\gamma_5\ell), \quad (6)$$

where $P_{L,R} \equiv (1 \mp \gamma_5)/2$, m_b is the b -quark mass, and the O'_i are obtained from the O_i through the replacements $P_L \leftrightarrow P_R$. The matrix elements can be expressed in terms of the B_s -meson decay constant f_{B_s} . Making the replacements $s \rightarrow d$ yields the Hamiltonian describing the $\bar{B}_d^0 \rightarrow \mu^+\mu^-$ decay.

Only the O_{10} operator is present in the SM, with a real Wilson coefficient C_{10}^{SM} which governs the predictions in (1) and (2). An outstanding feature of $\bar{B}_s^0 \rightarrow \mu^+\mu^-$ with respect to probing NP is the sensitivity to the (pseudo-)scalar lepton densities entering the $O_{(P)S}$ and $O'_{(P)S}$ operators, which have Wilson coefficients that are still largely unconstrained by the current data (see, for instance, [17]).

The calculation of the $B_s \rightarrow \mu^+\mu^-$ observables is discussed in detail in [16]. Let us here first have a brief look at the following time-dependent rate asymmetry, which requires tagging information and knowledge of the muon helicity λ :

$$\frac{\Gamma(B_s^0(t) \rightarrow \mu_\lambda^+\mu_\lambda^-) - \Gamma(\bar{B}_s^0(t) \rightarrow \mu_\lambda^+\mu_\lambda^-)}{\Gamma(B_s^0(t) \rightarrow \mu_\lambda^+\mu_\lambda^-) + \Gamma(\bar{B}_s^0(t) \rightarrow \mu_\lambda^+\mu_\lambda^-)} = \frac{C_\lambda \cos(\Delta M_s t) + S_\lambda \sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma}^\lambda \sinh(y_s t/\tau_{B_s})}. \quad (7)$$

The y_s entering this expression was introduced in (4), ΔM_s is the mass difference between the heavy and light B_s mass eigenstates, and

$$C_\lambda \equiv \frac{1 - |\xi_\lambda|^2}{1 + |\xi_\lambda|^2} = -\eta_\lambda \left[\frac{2|PS| \cos(\varphi_P - \varphi_S)}{|P|^2 + |S|^2} \right] \quad (8)$$

$$S_\lambda \equiv \frac{2 \text{Im } \xi_\lambda}{1 + |\xi_\lambda|^2} = \frac{|P|^2 \sin 2\varphi_P - |S|^2 \sin 2\varphi_S}{|P|^2 + |S|^2} \quad (9)$$

$$\mathcal{A}_{\Delta\Gamma}^\lambda \equiv \frac{2 \text{Re } \xi_\lambda}{1 + |\xi_\lambda|^2} = \frac{|P|^2 \cos 2\varphi_P - |S|^2 \cos 2\varphi_S}{|P|^2 + |S|^2} \quad (10)$$

with

$$P \equiv |P|e^{i\varphi_P} \equiv \frac{C_{10} - C'_{10}}{C_{10}^{\text{SM}}} + \frac{M_{B_s}^2}{2m_\mu} \left(\frac{m_b}{m_b + m_s} \right) \left(\frac{C_P - C'_P}{C_{10}^{\text{SM}}} \right) \quad (11)$$

$$S \equiv |S|e^{i\varphi_S} \equiv \sqrt{1 - 4 \frac{m_\mu^2}{M_{B_s}^2} \frac{M_{B_s}^2}{2m_\mu} \left(\frac{m_b}{m_b + m_s} \right) \left(\frac{C_S - C'_S}{C_{10}^{\text{SM}}} \right)}. \quad (12)$$

The P and S with their CP-violating phases $\varphi_{P,S}$ have been introduced such that $P = 1$ and $S = 0$ in the SM. It should be noted that $\mathcal{S}_{\text{CP}} \equiv S_\lambda$ and $\mathcal{A}_{\Delta\Gamma} \equiv \mathcal{A}_{\Delta\Gamma}^\lambda$ do not depend on the muon helicity λ . In (9) and (10), the NP contribution to the $B_s^0 - \bar{B}_s^0$ mixing phase $\phi_s = \phi_s^{\text{SM}} + \phi_s^{\text{NP}}$ was neglected, where the SM piece is given by $\phi_s^{\text{SM}} \equiv$

$2\arg(V_{ts}^*V_{tb}) \approx -2^\circ$. This effect can straightforwardly be included through $2\varphi_{P,S} \rightarrow 2\varphi_{P,S} - \phi_s^{\text{NP}}$. The LHCb data for CP violation in $B_s \rightarrow J/\psi\phi, J/\psi f_0(980)$ already constrain ϕ_s^{NP} to the few-degree level [11, 18], in contrast to the $\varphi_{P,S}$. Neglecting the impact of $\Delta\Gamma_s$, the CP asymmetries (7) were considered for $B_{s,d} \rightarrow \ell^+\ell^-$ decays within various NP scenarios in the previous literature [19]–[21].

As it is experimentally challenging to measure the muon helicity, we introduce

$$\Gamma(B_s^0(t) \rightarrow \mu^+\mu^-) \equiv \sum_{\lambda=L,R} \Gamma(B_s^0(t) \rightarrow \mu_\lambda^+\mu_\lambda^-), \quad (13)$$

and

$$\frac{\Gamma(B_s^0(t) \rightarrow \mu^+\mu^-) - \Gamma(\overline{B}_s^0(t) \rightarrow \mu^+\mu^-)}{\Gamma(B_s^0(t) \rightarrow \mu^+\mu^-) + \Gamma(\overline{B}_s^0(t) \rightarrow \mu^+\mu^-)} = \frac{\mathcal{S}_{\text{CP}} \sin(\Delta M_s t)}{\cosh(y_s t/\tau_{B_s}) + \mathcal{A}_{\Delta\Gamma} \sinh(y_s t/\tau_{B_s})}, \quad (14)$$

where $\Gamma(\overline{B}_s^0(t) \rightarrow \mu^+\mu^-)$ is defined in analogy to (13).

A measurement of the CP asymmetry in (14) would be most interesting as a non-vanishing value would immediately indicate new CP-violating phases, as illustrated recently in [22]–[24]. Unfortunately, since tagging and time information are required, this is still an experimental challenge. An expression analogous to (14) holds also for $B_d \rightarrow \mu^+\mu^-$, where y_d is negligibly small.

3 Branching Ratio

The first step for the experimental exploration of the $B_s \rightarrow \mu^+\mu^-$ decay is the extraction of a branching ratio from the untagged rate

$$\langle \Gamma(B_s(t) \rightarrow \mu^+\mu^-) \rangle \equiv \Gamma(B_s^0(t) \rightarrow \mu^+\mu^-) + \Gamma(\overline{B}_s^0(t) \rightarrow \mu^+\mu^-) \quad (15)$$

by ignoring the decay-time information [13, 14]:

$$\text{BR}(B_s \rightarrow \mu^+\mu^-)_{\text{exp}} \equiv \frac{1}{2} \int_0^\infty \langle \Gamma(B_s(t) \rightarrow \mu^+\mu^-) \rangle dt. \quad (16)$$

The experimental branching ratio in (3) refers to this branching ratio concept.

On the other hand, theorists usually consider and calculate the following CP-averaged branching ratio:

$$\text{BR}(B_s \rightarrow \mu^+\mu^-)_{\text{theo}} \equiv \frac{\tau_{B_s}}{2} \langle \Gamma(B_s(t) \rightarrow \mu^+\mu^-) \rangle \Big|_{t=0}, \quad (17)$$

where the B_s^0 – \overline{B}_s^0 oscillations are “switched off” by choosing $t = 0$. The SM prediction in (1) actually refers to this branching ratio definition and satisfies

$$\frac{\text{BR}(B_s \rightarrow \mu^+\mu^-)_{\text{theo}}}{\text{BR}(B_s \rightarrow \mu^+\mu^-)_{\text{SM}}} = |P|^2 + |S|^2. \quad (18)$$

As was pointed out in [16], the experimental branching ratio (16) can be converted into the theoretical branching ratio (17) with the help of the following expression:

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{theo}} = \left[\frac{1 - y_s^2}{1 + \mathcal{A}_{\Delta\Gamma} y_s} \right] \text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{exp}}, \quad (19)$$

where it is essential that $\mathcal{A}_{\Delta\Gamma} \equiv \mathcal{A}_{\Delta\Gamma}^\lambda$ does actually not depend on the muon helicity.

Looking at (10)–(12), we observe that NP may affect $\mathcal{A}_{\Delta\Gamma}$ through the Wilson coefficients so that this observable is currently unknown. However, within the SM, we have the theoretically clean prediction of $\mathcal{A}_{\Delta\Gamma}^{\text{SM}} = +1$. Using (19), we hence rescale the theoretical SM branching ratio in (1) by a factor of $1/(1 - y_s)$, yielding

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{SM}}|_{y_s} = (3.54 \pm 0.30) \times 10^{-9} \quad (20)$$

for the value of y_s in (4). This is the SM reference value for the comparison with the experimental branching ratio (3).

4 Effective Lifetime

In the future, once the $B_s \rightarrow \mu^+ \mu^-$ signal has been well established and more data become available, also the decay-time information can be taken into account in the experimental analysis. This will allow a measurement of the effective lifetime

$$\tau_{\mu^+ \mu^-} \equiv \frac{\int_0^\infty t \langle \Gamma(B_s(t) \rightarrow \mu^+ \mu^-) \rangle dt}{\int_0^\infty \langle \Gamma(B_s(t) \rightarrow \mu^+ \mu^-) \rangle dt} = \frac{\tau_{B_s}}{1 - y_s^2} \left[\frac{1 + 2 \mathcal{A}_{\Delta\Gamma} y_s + y_s^2}{1 + \mathcal{A}_{\Delta\Gamma} y_s} \right], \quad (21)$$

so that also the observable

$$\mathcal{A}_{\Delta\Gamma} = \frac{1}{y_s} \left[\frac{(1 - y_s^2) \tau_{\mu^+ \mu^-} - (1 + y_s^2) \tau_{B_s}}{2 \tau_{B_s} - (1 - y_s^2) \tau_{\mu^+ \mu^-}} \right] \quad (22)$$

can be extracted from the data [13, 16]. The effective lifetime allows the conversion of the experimental $B_s \rightarrow \mu^+ \mu^-$ branching ratio into its theoretical counterpart through

$$\text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{theo}} = \left[2 - (1 - y_s^2) \frac{\tau_{\mu^+ \mu^-}}{\tau_{B_s}} \right] \text{BR}(B_s \rightarrow \mu^+ \mu^-)_{\text{exp}}. \quad (23)$$

This relation holds no matter whether NP contributions are present in $B_s \rightarrow \mu^+ \mu^-$ or whether this decay is fully governed by the SM.

The effective $B_s \rightarrow \mu^+ \mu^-$ lifetime and the extraction of $\mathcal{A}_{\Delta\Gamma}$ from untagged data samples are exciting new aspects for the exploration of the $B_s \rightarrow \mu^+ \mu^-$ decay at the high-luminosity upgrade of the LHC. An extrapolation from current measurements of the effective $B_s \rightarrow J/\psi f_0(980)$ and $B_s \rightarrow K^+ K^-$ lifetimes by the CDF and LHCb collaborations to $\tau_{\mu^+ \mu^-}$ indicates that a precision of 5% or better may be feasible [16]. Detailed experimental studies are strongly encouraged.

5 Constraints on New Physics

The $\Delta\Gamma_s$ affects also the NP constraints that can be obtained by comparing the experimental $B_s \rightarrow \mu^+\mu^-$ branching ratio information with the SM picture [16]:

$$R \equiv \frac{\text{BR}(B_s \rightarrow \mu^+\mu^-)_{\text{exp}}}{\text{BR}(B_s \rightarrow \mu^+\mu^-)_{\text{SM}}} = \left[\frac{1 + y_s \cos 2\varphi_P}{1 - y_s^2} \right] |P|^2 + \left[\frac{1 - y_s \cos 2\varphi_S}{1 - y_s^2} \right] |S|^2. \quad (24)$$

Using (1) and (3) yields $R = 1.0_{-0.4}^{+0.5}$, where the errors have been added in quadrature.

The R ratio can be converted into ellipses in the $|P|$ - $|S|$ plane which depend on the CP-violating phases $\varphi_{P,S}$. Since the latter quantities are unknown, R fixes actually a circular band with the upper bounds $|P|, |S| \leq \sqrt{(1 + y_s)R}$. As the experimental information on R does not allow us to separate the S and P contributions, still significant NP contributions may be hiding in the $B_s \rightarrow \mu^+\mu^-$ channel.

This situation can be resolved by measuring the effective lifetime $\tau_{\mu^+\mu^-}$ and the associated $\mathcal{A}_{\Delta\Gamma}$ observable, since

$$|S| = |P| \sqrt{\frac{\cos 2\varphi_P - \mathcal{A}_{\Delta\Gamma}}{\cos 2\varphi_S + \mathcal{A}_{\Delta\Gamma}}} \quad (25)$$

fixes a straight line through the origin in the $|P|$ - $|S|$ plane. For illustrations, the reader is referred to the figures shown in [16].

In the most recent analyses of the constraints on NP parameter space that are implied by the experimental upper bound on the $B_s \rightarrow \mu^+\mu^-$ branching ratio for various extensions of the SM, authors have now started to take the effect of $\Delta\Gamma_s$ into account (see, for instance, [22]–[24] and the papers in [25]–[33]).

6 Conclusions

We live in exciting times for analyses of rare leptonic B decays. While the experimental upper bound for the $B_d \rightarrow \mu^+\mu^-$ channel is still about an order of magnitude above the SM expectation, LHCb has recently reported the first evidence for $B_s \rightarrow \mu^+\mu^-$ at the 3.5σ level, with a first experimental branching ratio of $(3.2_{-1.2}^{+1.5}) \times 10^{-9}$.

In view of the sizable decay width difference $\Delta\Gamma_s$ of the B_s -meson system, we have to deal with subtleties in the extraction of B_s branching ratio information from the data, but we get also new observables, encoded in effective decay lifetimes. This is also the case for the $B_s \rightarrow \mu^+\mu^-$ decay, where the theoretical SM branching ratio in (1) has to be rescaled by $1/(1 - y_s)$ for the comparison with the experimental branching ratio, resulting in the SM reference value of $(3.54 \pm 0.30) \times 10^{-9}$. The sizable value of $\Delta\Gamma_s$ propagates also into the constraints on NP parameters that can be obtained from the $B_s \rightarrow \mu^+\mu^-$ branching ratio information, and can be included by means of the formulae presented above.

The future measurement of the effective $B_s \rightarrow \mu^+ \mu^-$ lifetime will allow the inclusion of the $\Delta\Gamma_s$ effect in the conversion of the experimental information into the theoretical branching ratio. Furthermore, the $\mathcal{A}_{\Delta\Gamma}$ encoded in $\tau_{\mu^+ \mu^-}$ provides a new, theoretically clean NP probe that may still show large NP effects, in particular for scenarios with new contributions to the Wilson coefficients of the four-fermion operators with (pseudo-)scalar $\ell^+ \ell^-$ densities. These features offer an exciting new topic for the next round of precision at the high-luminosity upgrade of the LHC.

It will be most interesting to monitor the future experimental progress on the exploration of $B_{s(d)} \rightarrow \mu^+ \mu^-$ decays in this decade and how their increasingly more stringent constraints on the parameter space of specific NP models will complement other flavor probes and the direct searches for NP at the LHC.

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